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FIELD PROGRAM OPERATIONS - TURBULENCE AND GUST FRONT STUDIES.(U)
NOV 81 J T LEE, R J DOVIAK DT-FA01-80-Y-10524

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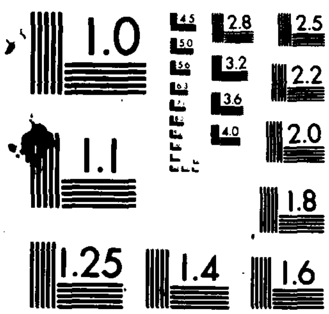

MICROCOPY RESOLUTION TEST CHART

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Systems Research &
Development Service
Washington, D.C. 20590

Field Program Operations - Turbulence and Gust Front Studies

J. T. Lee
R. J. Doviak

November 1981

Final Report

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16. Abstract

The 1980 Spring Observation Program extended from April 15 to June 19 at the National Severe Storms Laboratory, Norman, Oklahoma. Aircraft, rawinsonde network, mesoscale surface network, low-level wind shear alert system at Will Rogers World Airport, 444 m instrumented tower and satellite observations augmented a conventional weather radar and a new, dual Doppler weather radar system to obtain concurrent data on weather hazards to aircraft. Storm days and data acquired are detailed.

An objective for the spring program was to determine the characteristics and detectability of turbulence, wind shear and other aircraft operational weather hazards using indirect (radar) probes. The South Dakota School of Mines T-28 aircraft and the National Aeronautics and Space Administration's F-106 aircraft made thunderstorm penetrations during Doppler radar and lightning operations. Data obtained are discussed, and the analysis of a turbulence case and two gust front cases are presented. These indicate the Doppler radar's potential use to detect and dimensionalize aviation weather hazards both in-cloud and in optically clear air. These studies and additional ones now in progress will provide material for guideline development as to siting and uses of the Next Generation Radar (NEXRAD) in aviation-related situations.

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METRIC CONVERSION FACTORS

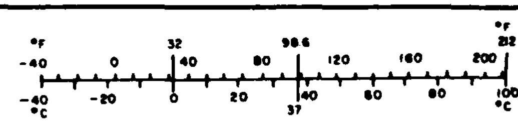
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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List of Abbreviations and Symbols

ACCAS	=	altocumulus castellatus
AGL	=	above ground level
CIM	=	NSSL radar site, Page Field, Oklahoma City
cm	=	centimeter
CST	=	Central Standard Time
dBZ	=	radar reflectivity factor in decibels
F	=	temperature in Fahrenheit
ft	=	feet
g	=	grams
I	=	radar video signal Inphase phase
kg	=	kilogram
km	=	kilometer
kt	=	knot
m	=	meter
MSL	=	mean sea level
n mi	=	nautical mile
NRO	=	NSSL radar site at Norman, OK
PPI	=	plan position indicator
PRT	=	pulse repetition time
Q	=	radar video signal Quadrature phase
s	=	second
SAM	=	Surface Automated Meteorological network
TAS	=	true airspeed
VHF	=	very high frequency
g	=	acceleration due to gravity
μs	=	microsecond

FIELD PROGRAM OPERATIONS - TURBULENCE

AND GUST FRONT STUDIES

J. T. Lee and R. J. Doviak

1. Introduction

The 1980 Spring Observation Program, hosted by the National Severe Storms Laboratory (NSSL), from April 15 to June 19, 1980, was substantially reduced from the Severe Environmental Storms and Mesoscale Experiment (SESAME) program in 1979. The prime purposes for conducting the 1980 observation were: 1) to emphasize coordination of storm electricity measurements made by the recently formed Storm Electricity Group at NSSL, 2) to make observations in the prestorm environment using NSSL's Doppler radars modified for this purpose, 3) support data collection for the Federal Aviation Administration (FAA) experiments on storm hazards to aircraft, and 4) support a hail collection experiment. Furthermore, storm scale measurements on severe thunderstorms of tornadic potential within the NSSL dual Doppler network are rare enough to warrant data collection during the spring when these events are most likely.

A number of outside groups were represented in the 1980 program. The University of Oklahoma performed experiments for lightning echo studies using a recently installed 23 cm radar, and National Aeronautics and Space Administration (NASA) flew an instrumented F106 jet aircraft to measure turbulence and storm electricity. Under FAA auspices, the Massachusetts Institute of Technology's (MIT) Lincoln Laboratory arranged to have South Dakota School of Mines and Technology fly their armored T-28 in thunderstorms. Thus, researchers at Lincoln Laboratory and NSSL have data from the T-28 in addition to NASA's F-106 aircraft data for comparison with in situ measurements with NSSL's Doppler radars' remotely inferred turbulence. The National Center for Atmospheric Research (NCAR) arranged to have one of its hail collection vehicles and personnel to sample hailfall. Researchers from Purdue University came to Oklahoma to measure corona current, and from the State University of New York at Albany and New Mexico Institute for Mining and Technology to measure optical emissions from lightning. The University of Mississippi participated by making in situ electrical measurements near tornado cyclones, and an investigator from the National Hurricane and Experimental Meteorology Laboratory in Miami operated lightning ground strike location equipment. The program was supported by the FAA, NASA, Office of Naval Research (ONR), and Nuclear Regulatory Commission (NRC), as well as by NOAA.

Figure 1.1 diagrams the various equipment utilized for the 1980 observational period. Figure 1.2 shows the location of the fixed surface network. There are three radars at NSSL in Norman, Oklahoma: NRO Doppler, WSR-57, and a 23-cm lightning echo radar. These are colocated with the storm electricity building that houses the electric field and other sensors, and a very high frequency (VHF) lightning mapper. The second Doppler radar (CIM Doppler) and VHF mapper are located at Page Airfield (formerly Cimarron Field) 40 km to the northwest of NSSL. The rawinsonde network was composed of 4 sites to provide sounding data. Stations were manned by the U. S. Air Force Sixth Weather Squadron (Mobile),

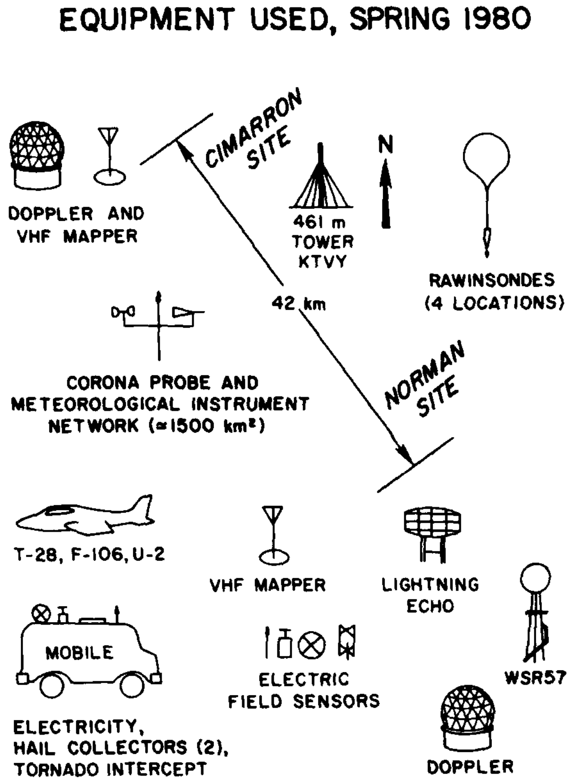

Figure 1.1 Equipment used in the 1980 Spring Program

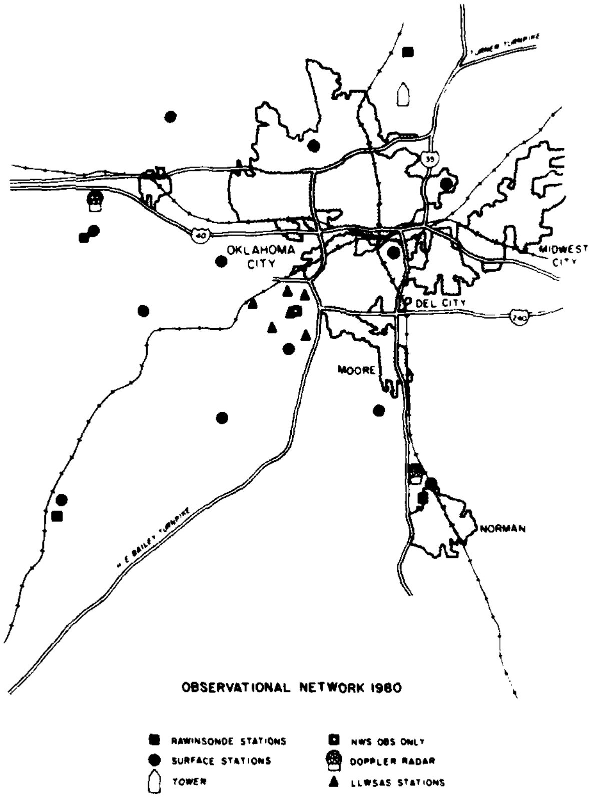

Figure 1.2 Location of the 1980 ground based observational network.

and, to minimize operational costs, were located within commuting distance of Tinker AFB. The surface network, also deployed over a limited area (Fig. 1.2) to reduce costs, consisted of 12 stations within commuting distance of NSSL. With the aid of the National Weather Service (NWS) and its cooperative observers, NSSL's hygrothermographs recorded temperature and relative humidity at six sites around central Oklahoma. In addition, wind data were recorded at six Low Level Wind Shear Alert S..tem (LLWSAS) stations maintained by the FAA for detection of wind shift lines that might affect aircraft operations at Will Rogers World Airport. The KTVY television tower was also instrumented by NSSL at seven levels.

Although the spring weather was wet, Oklahoma had an unusually low incidence of severe weather. Only on six occasions (May 1, 11, 17-18, 29, and June 16 and 19) were data obtained on severe thunderstorms in central Oklahoma. Table 1.1 lists the number of hours when data were collected in support of the aviation program.

2. Brief Description of Equipment Used

2.1 Radars

NSSL operates and maintains three 10-cm radars. Two are Dopplers spaced 41 km apart; one (NRO) located at NSSL and the second (CIM) at Page Field (formerly Cimarron Field). The third radar is an incoherent surveillance weather radar (WSR-57) located at NSSL. A detailed description of these radars is contained in NSSL's Tech Memo 91, Spring Program 1980.

Table 1.1. Number of Hours of Data Collection for Aviation Programs.

	APR	MAY							JUNE								TOTAL
	24	7	11	17	18	20	29	30	3	4	6	8	9	16	17	19	HOURS
I. GUST FRONT (Lee/Brandes)			N	N,C			N							N,C		N,C	
Radars			1½	>1 1			1							½		>1	5
Aircraft																	
Surface			T,S	L T,S			T,S							L T,S		T,S	
Rawinsonde																✓	
II. TURBULENCE (Lee/Zrnic')					N	N,C			N	N	N	N	N	N	N		
Radars					1½	1½			1½ F	1½ F	1 F	1½ F	1 F	1 F	½ F		9
Aircraft					28	28			106	106	106	106	106	106	106		
III. LIFETIME (Zrnic')	N ½													N,C ½	N <½		≃1½
IV. CLUSTER/TRACK (Wilk/Crane)	C	N,C	N	N		C	N	N						N	N	C	
Radars	2½	4	1½	1		2	6	1						1	½	1	20½

C = CIM. DOP. T = TOWER L = LLWAS
N = NRO DOP. S = S.A.M.

2.1.1 Doppler Radars

The NRO and CIM radars are very similar. Each radar records the three moments (reflectivity intensity, mean velocity, and spectrum width) of the Doppler spectrum at all ranges, and the time series samples of the Inphase (I) and Quadrature (Q) phase video signals sampled simultaneously at 16 range locations. There are several options in transmitting pulses: (a) A uniform train for Doppler spectral analysis, (b) an interlaced pulse repetition time (PRT) (dual sampling mode) for automated range de-aliasing of multiple trip targets and flagging of range overlaid echoes, (c) long transmitted pulse width (3-5 μs) for maximum sensitivity to detect clear air echoes and (d) a high PRF mode (NRO only) for measuring tornadic speeds.

Typical antenna scan rates are 6-10° s^{-1}; angular resolution is about 0.8°, and range resolution is as fine as 150 m, but depends on transmitter mode used.

2.1.2 WSR-57

This incoherent radar has an angular resolution of about 2° and a range resolution of 1 km (for most experiments). It provides reflectivity estimates and scans at a rate of 18° s^{-1} in azimuth and automatically steps in elevation at increments selected by the WSR-57 operator. This radar is usually operated automatically in a surveillance mode. It is interfaced to a transponder indentification radar used to guide aircraft into data collection regions.

2.2 VHF Mapping System

A wide band VHF system, employing time-difference-at-arrival techniques, provides azimuth and elevation angles to individual sources of electromagnetic impulses from lightning discharges. Acceptable elevation angles are within 45° above the horizon, while the azimuth angles are limited to a 60° sector, selectable in 30° increments. Angles are determined to 0.5° accuracy and lightning generated impulse sources within a nominal 60 km (32 n mi) range can usually be detected. Maximum instantaneous rate of reception is 16,000 per second. Data are recorded on 9-track magnetic tape and a real-time azimuth-elevation display is available to assist in detecting and tracking thunderstorms. Simultaneous observations are made near NSSL's Norman and Cimarron Doppler radars.

2.3 Storm Electricity Building (SEB)

The SEB serves as a central location for acquisition of storm electricity data and coordination with other areas of experimental data collection, e.g., Doppler facility, storm intercept control, etc. Instrumentation located at the SEB and near it in the field is used to measure various electrical phenomena such as electric field changes associated with lightning, optical transients from lightning, and video documentation of lightning and associated storms. Data are recorded on analog magnetic tape with time code synchronized to the National Bureau of Standards (NBS) radio station WWV time signals.

2.4 The 23-cm Lightning Path Radar

A 23-cm radar is located at the SEB for acquisition of radar echoes from lightning. The lightning radar echoes are recorded on the same magnetic tape as the electricity phenomena and on a separate video cassette recorder. Because of its long-range capability for observing lightning [200 km (108 n mi)], this radar is also used to acquire data on storms being studied with the Mobile Electric Laboratory.

2.5 The Stationary Automated Mesonetwork

Twelve meteorologically instrumented stations were used in Spring 1980, and these were located close to NSSL so that they could be routinely serviced without additional manpower cost. Each site provided measurements of wind speed and direction, wet and dry bulb temperatures, pressure, rainfall, and corona current. One-second samples were averaged for one minute, and these were recorded on cassette magnetic tapes.

2.6 Rawinsondes

The 1980 spring mesometeorological rawinsonde network was established at four locations surrounding Oklahoma City (see Fig. 1.2). GMD-1 rawinsonde equipment was used to obtain soundings with a VIZ Manufacturing Company "ACCU-LOK" instrument. These instruments were factory calibrated (pre-baselined). Personnel from the U.S. Air Force Sixth Weather Squadron (Mobile) located at Tinker AFB in Oklahoma City manned and operated each of the four sites.

Specialized data acquisition and processing procedures were used to bring data to the laboratory in near real time. Each site was equipped with a standard ASR-33 teletypewriter with paper tape punch and acoustic coupler, and standard commercial telephone. At Tinker AFB, a Model 3610 computer system was used for processing the raw rawinsonde data. At NSSL an HP 9825A received the output data from the Model 3610 CPU and plotted the data in graphic form on a standard skew T, log p diagram.

A total of 176 soundings were taken during the period 1 May through 19 June 1980.

2.7 Aircraft

2.7.1 T-28

A T-28 aircraft was operated by the Institute of Atmospheric Sciences, South Dakota School of Mines and Technology in support of the joint FAA-NSSL aircraft turbulence program. The Massachusetts Institute of Technology's Lincoln Laboratory was also a partner in the program.

The T-28 is an extensively modified single-engined propeller-driven military training aircraft. The structure of the aircraft has been strengthened and all leading edges including the wing and tail surfaces are armor plated to protect the aircraft from hail damage. The aircraft was instrumented as indicated in Table 2.1. Penetration true airspeed (TAS) was 90 to 95 $m \cdot s^{-1}$ (180-190 kts) with a flight duration 1-1/2 to 2 hours. The aircraft arrived in Norman on 12 May. The T-28 program was terminated on 20 May when, after a successful mission, the aircraft sustained damage to the nose wheel and engine caused by running off a taxiway onto soft turf.

Table 2.1. T-28 Instrumentation.

	Measurement	Instrument
1.	Temperature	Rosemount and NCAR reverse plan
2.	Static pressure	Rosemount static pressure transducer
3.	Air speed	Rosemount sensor
4.	Vertical veloctiy	Rate of climb
5.	Altitude	Aircraft system
6.	Differential pressure	Rosemount differential pressure
7.	Vertical acceleration	Humphrey vertically stabilized accelerometer
8.	Roll and pitch	Humphrey system
9.	Peak accelerations	IAS design
10.	Heading	Aircraft compass system
11.	Position	Two DME and one VOR system

2.7.2 F-106B

The F-106B aircraft, supplied and flown by NASA, was part of the severe storm program of NASA, FAA, and NSSL. This single-engined jet fighter is instrumented as indicated in Table 2.2. The objective of the program is to improve the state-of-the-art of severe storm hazard protection, storm detection, and avoidance, and design of aircraft for those hazards which cannot be reasonably avoided. The hazards include lightning, turbulence, wind shear, hail, and extreme precipitation rates. In the first phase of the 1980 program, turbulence and lightning were the major interest areas.

The F-106B arrived at Tinker AFB on 20 May and returned to Langley Research Center, Virginia, on 19 June. During this time, 9 flights were made to penetrate thunderstorms. The aircraft flew at a TAS near 195 $m \cdot s^{-1}$ and had just over a one-hour flight duration. During these nine flights, the aircraft made 33 penetrations at altitudes indicated in Table 2.3.

2.7.3 U-2

The NASA U-2 is a single-engined jet aircraft designed for high altitude (above 60,000 ft MSL) flights. Cruising speed is around a TAS of 150 $m \cdot s^{-1}$ (290 kt). Besides the normal navigational and aircraft instrument recordings, three special systems for the lightning experiments were included as follows:

1) a slow antenna
2) a Night/Daytime Optical Survey of Lightning and convective phenomena experiment (NOSL) sensor
3) a TV spectrometer system

Table 2.2. F-106B Measurements on Aircraft Instrumentation System for Storm Hazards '80.

Measurement	Range	Required Flat to Freq. Resp., Hz	σ Error Accuracy	Resolution	Notes
Stormscope dots	-	-	-	-	Serial PCM
Stormscope clear	-	-	-	-	Discrete
Stormscope range buttons	-	-	-	-	Discrete
Pilot event	-	-	-	-	Pilot's control stick-discrete
Copilot event	-	-	-	-	AIS panel-discrete
Static pressure	0-15 psia	3	0.07 psia	0.0004 psia	Quartz transducer-under-nose pitot-static head
Dynamic pressure	0-3 psid	6	0.03 psid	0.0004 psid	Quartz transducer-gust boom for p_t
Angle of attack	±15°	10	0.09°	0.015°	Flow vane on gust boom
Angle of side slip	±15°	10	0.09°	0.015°	Flow vane on gust boom
Pitch rate	±1 s^{-1}	5	0.01s^{-1}	0.004s^{-1}	Mounted by weapons bay
Roll rate	±1 s^{-1}	5	0.01s^{-1}	0.004s^{-1}	Mounted in weapons bay
Yaw rate	±1 s^{-1}	5	0.01s^{-1}	0.004s^{-1}	Mounted in weapons bay
Long. Accel.	±1g	10	0.01g	0.004g	Mounted at CG; no good
Lat. Accel.	±1g	10	0.01g	0.004g	Mounted at CG; no good
Norm. Accel.	4 to -2g abs	10	0.01g	0.012g	Mounted at CG
Total air temp.	35° to -75°C	0.5	0.3°C	0.205°C	Probe beneath nose
Stick-Lateral	Full travel	N/A	-	-	Pilot's control stick
Stick-Long.	Full travel	N/A	-	-	Pilot's control stick
Pitch attitude	15°	5	0.03°	0.015°	INS platform (DELCO Carousel)-contin. synchro.

Table 2.2. (Cont'd)

Measurement	Range	Required Flat to Freq. Resp., Hz	σ Error Accuracy	Resolution	Notes
Roll attitude	±30°	5	0.1°	0.03°	INS platform-contin. synchro.
True Heading	0°-360°	-	-	0.18°	INS platform-contin. synchro.
Vertical accel.	3 to -1g	5	0.005°g	0.008g	INS platform-accel.
N-S ground speed	4096 ft/s	50 ms	3 ft/s	0.001 ft/s	INS platform-digital
E-W ground speed	4096 ft/s	50 ms	3 ft/s	.001 ft/s	INS platform-digital
Latitude	±90°	600 ms	1nmi/h	0.14arcsec	INS platform-digital
Longitude	±180°	600 ms	1nmi/h	0.14arcsec	INS platform-digital
Track angle	±(0°-180°)	600 ms	-	0.14arcsec	INS platform-digital
Dist. to go	64×10^6 ft	600 ms	-	16 ft	INS platform-digital
True heading	0°-360°	50 ms	-	0.14arcsec	INS platform-digital-should be used for data
Bearing to dest.	0°-360°	600 ms	-	0.14arcsec	INS platform-digital
ACE events	-	-	-	-	24 ACE bottles-discretes
Audio	-	-	-	-	Transmit, receive and intercom
Rudder pedals	Full range	-	-	-	Pilot's pedals

Table 2.3. 1980 F-106 Thunderstorm Penetration Altitude Distribution.

Penetration Altitude (MSL)	No. of Penetrations
23,000 ft	2
22,000 ft	2
20,000 ft	8
16,000 ft	7
15,000 ft	9
14,000 ft	2
13,000 ft	3

The U-2 was available for flights during the period May 10 through May 20. One objective was to determine the feasibility of locating lightning from above the storm leading eventually to detection by satellite. On May 15, the U-2 flew over a heavy rain-producing system in central and southwestern Oklahoma and later over more active thunderstorms in Texas. Several flashes were recorded.

2.8 Cloud-Ground Lightning Location System

The cloud-ground (CG) lightning location system was operated from April 12 until June 1. This instrumentation provides the time, location, peak field strength (current) and number of component strokes for each CG flash which lowers negative charge within about 200 km of Norman. The system consists of three remote direction finders (DF's) which independently determine the azimuth angle to the CG flash. These data are transmitted back to a central processing unit by leased phone lines. The central processing unit or position analyzer computes the intersection point of the azimuth angles and prints the data on digital magnetic tape, hard-copy printer and plotter in real time. These devices were located in the storm electricity building.

2.9 Meteorological Tower

The 461 m (1512 ft) KTVY television antenna tower has been used as a multi-level boundary sensor facility since 1966. Currently, it is instrumented at seven levels--7, 26, 45, 89, 177, 266, and 444 m (23, 85, 146, 296, 581, 873, 1459 ft). Data are routinely recorded on magnetic tape. A 10-second sample interval is used during non-storm conditions and a 1.3-second interval during storm periods. Two gust front occurrences were recorded at the 1.3-s rate on 17 May and 16 June. Gusts over 25 $m \cdot s^{-1}$ (50 kt) were recorded several times during the season.

2.10 Low-Level Wind Shear Alert System (LLWSAS)

LLWSAS is a real-time, computer-controlled, surface-based wind sensor system using radio telemetry as a communication link. The system installed by the FAA at Will Rogers International Airport consists of six wind sensor sites located as shown in Figure 1.2. All sites use the vector vane-type sensor system mounted about 20 ft AGL. The wind speed and direction data are collected at 7-second intervals and processed by the computer for display in the airport air traffic

control tower. Arrangements were made with the FAA to record the data before it was processed whenever severe weather was expected to cross the airport. Recording was sequentially accomplished using an AXIOM Corp. EX801 recorder. These data were then transferred to punched card for further analysis using developed computer programs. The LLWSAS provides a small mesoscale wind observation network nested within the SAM network and, since it is airport-centered, provides ground truth for covering Doppler radar operations. Data were obtained for two gust front cases--17 May 1980 and 16 June 1980.

3. Data Collection

Aircraft operations began on 9 May and continued through 18 June. Surface and radar data collection began on 1 May and continued through 23 June. Appendix A is a condensed daily log covering the period. Appendix B is a log of aircraft activity.

3.1 Aircraft Data

3.1.1 T-28 Aircraft

The aircraft flew two missions; one on 18 May and the other on 20 May. A ground accident terminated the program. The South Dakota School of Mines is responsible for the T-28 data processing. Data for the second flight have been completely processed and furnished to Lincoln Laboratory. Portions of the first flight have also been sent to Lincoln Laboratory.

3.1.2 F-106B Aircraft

Nine thunderstorm missions were flown with a total of 33 penetrations made during these flights. Appendix B provides a brief summary of each flight. No thunderstorms with reflectivity factor equal to or greater than 40 dBZ occurred during daylight hours between 30 May and 15 June. The F-106 flights on 16 and 17 June were in moderate-to-strong thunderstorm areas. These last two days were the most productive of the F-106B flights program. The aircraft encountered moderate-to-severe turbulence as reported by the pilot, and was struck three times by lightning. Prior to 16 June, only light turbulence had been encountered and no lightning strikes had been recorded. The F-106B data are being processed by NASA, and as soon as these data are available, they will be furnished to NSSL and Lincoln Laboratory.

3.2 Radar Data

3.2.1 Doppler Radar

Table 3.1 lists times when the Doppler radar was operating and data were recorded. Data, including reflectivity, mean velocity, and spectrum width, are recorded on magnetic tape. Copies of these data tapes for all flights have been furnished Lincoln Laboratory. No dual-Doppler data for the penetrations are available.

3.2.2 WSR-57

Data were recorded on film for each penetration flight. Copies of the film which contain both the transponder returns and the weather returns have been furnished to Lincoln Laboratory. The T-28 and F-106B flight tracks, as

Table 3.1 1980 Norman and Cimarron Doppler Radar Observations (times to the nearest 5 min.).

DATE	NORMAN TIME PERIOD (CST)	CIMARRON TIME PERIOD (CST)
May 1	1945→2130	
May 2	1300→1630	
May 7	0630→0650; 1030→1230; 1700→1915	1000→1100; 1200→1230; 1500→1700
May 11	1920→2335	2100→2300
May 12	1020→1325	0830→1100
May 15	1430→1625	
May 17	2115→0000	2225→0000
May 18	0000→0245; 1500→1700	0000→0220
May 19	1300→1515	
May 20	0935→1125; 1435→1555	1040→1125; 1335→1550
May 23	0505→1120	
May 29	0020→0235; 1230→2140	1340→1905
May 30	0620→2055	0930→2050
June 3	1430→1515	
June 4	0500→1500	
June 6	1715→0800; 1330→1400	
June 8	0920→1055	
June 9	0640→0920	
June 11	0500→1140	1400→1500
June 16	0815→2215	1000→2210
June 17	0815→1815	1000→1810
June 18	1400→1430	1300→1500
June 19	1530→0100	0850→0855; 1530→0015

determined from the transponder returns, have been completed and copies furnished Lincoln Laboratory and NASA Langley.

3.3 Surface Data

The 12-station surface networks began operation in early May. Operational problems, while not as great as in 1979, still persisted, and complete data sets were not obtained--there are a number of sets with 9 of the 12 stations providing data. In addition, the LLWSAS system at Will Rogers Airport was recorded on 17 May and 16 June as gust fronts were in the area.

3.4 Tower

The instrumented KTVY-TV television tower was in operation 15 April to 23 June. The seven levels, surface to 444 m (1,459 ft), were recorded routinely at 10 s intervals except during several gust front situations when data were recorded at about 1 s intervals. Data are processed and archived on magnetic tapes.

3.5 Rawinsonde Data

176 soundings were taken by the network stations. These data are processed and archived on magnetic tape.

4. Data Analyses

As mentioned previously, thunderstorm activity was below normal in 1980. That, coupled with data processing delays, provides only a few cases for this report. These are as follows:

4.1 June 16, 1980 - Aircraft Turbulence

Thunderstorms were already active in the early morning and were moving slowly east-southeastward. The F-106 aircraft crew was alerted and given an estimated takeoff time of around 0845 CST, when the storms were forecast to be within Doppler range. The aircraft took off at 0853 CST and was vectored toward the storms then at 340°, 130 km (70 n mi) from Norman. Maximum reflectivity factor in the storms was near 55 dBZ. The first penetration began at 0905 CST, roughly ten minutes after takeoff. Six penetrations were made during which the pilot reported heavy turbulence, some heavy rain, and frequent lightning. No lightning strikes to the aircraft were observed or recorded. Aircraft flight altitude was 4.6 km (15,000 ft), and the aircraft was on a southbound heading (Figure 4.1a). A point-by-point comparison of Doppler spectrum width with the departure of aircraft's vertical acceleration from that of gravity is shown in Figure 4.1b. Accelerations are maximum deviations from $1g$ over 5s intervals--corresponding roughly to 1 km (0.5 n mi) of flight. Maximum and average spectrum width over 1 km flight segments are both shown as a function of segment position. The widths are from radar resolution volumes that contained the aircraft path, and owing to the plane's constant altitude, two elevation angles were used for obtaining Figure 4.1b. As in previous studies, the turbulence plot matches the spectrum width quite well, considering that up to two minutes of time difference exists between the aircraft measurement and the radar records at the plane altitudes. Corrections due to storm motion over such time differentials have been incorporated into the analysis.

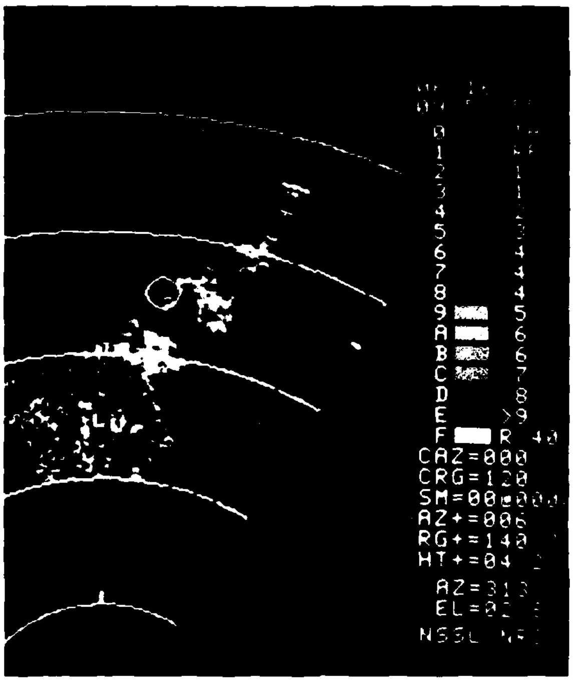

Figure 4.1a *Photograph of the Norman Doppler PPI spectral width display at 0953:12 June 16, 1980. Circle with dot at center indicates approximate position of southbound aircraft. Center of radar beam at circle is at an altitude of 4.2 km (13,800 ft). 40 km (22 n mi) range marks. Spectrum width legend on right side of scope is in m s^{-1}.*

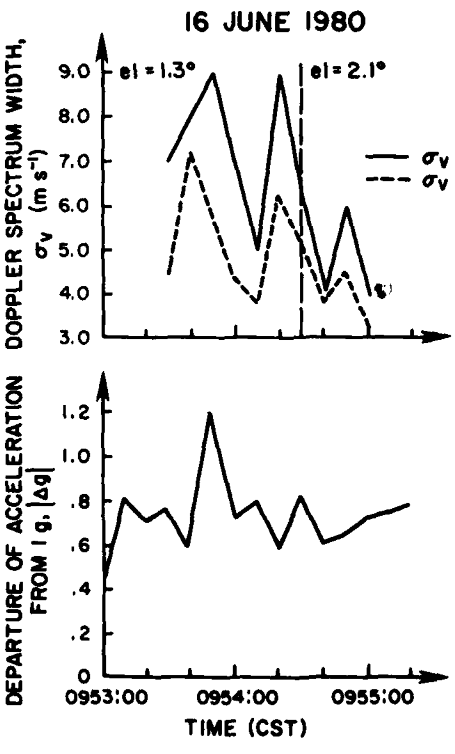

Figure 4.1b *Time history of turbulence encountered by NASA F-106B aircraft flying at 4 km (13,000 ft) on June 16, 1980. Upper portion of figure is corresponding Norman Doppler radar data along aircraft track which is depicted as a time history in lower portion of figure.*

4.2 May 11, 1980 -- Gust Front

Morning data were not very encouraging for the later development of severe thunderstorms. Even though the upper flow was southwesterly and strong, the nearest significant shortwave trough was far to the west in Arizona. Numerical forecast guidance suggested that only a very weak wave would affect Oklahoma by evening. Furthermore, morning radiosonde data from Oklahoma City showed an extremely shallow layer of moist air (~30 mb deep), with a 100 mb mixed layer value of only about 7.5 g kg^{-1}. Analysis of 850 mb indicated that even drier air was to be found at all upwind stations. A surface dryline in western Oklahoma was expected to mix rapidly eastward by afternoon and a triple point, i.e., dryline intersection with a cold front (in northern Oklahoma in the morning) was anticipated over Tulsa.

By midafternoon the dryline had still not moved eastward and was found on a line from Stillwater to Hobart. Dewpoints to the east of the boundary remained in the low 70's (°F). An unidentified moisture source was apparent. Evening sounding data showed more than 14 g kg^{-1} of moisture in the deepened Oklahoma City boundary layer. Moreover, at approximately 1700 CST, a large field of very well-defined altocumulus castellatus (ACCAS) moved rapidly into central Oklahoma, indicating the presence of a shortwave trough aloft of a much greater intensity than expected.

Shortly after the appearance of the ACCAS field, very intense storms formed in central Oklahoma along the dryline. The activity produced several severe storm reports and three tornadoes. A radar echo "thin line" was detected at about 2230 CST, and Figure 4.2a shows the reflectivity field measured by the Doppler radar 15 minutes later. The thin line is often associated with gust fronts so these data were analyzed to determine the wind shears along this line which propagated over 80 km (43 n mi) away from its parent storm.

The gust front is probably one of the most insidious hazards to aircraft because it can exist in the clear air tens of kilometers away from the thunderstorm that spawned it. Yet it can harbor shear forces that can be destructive to aircraft and crew when they are unaware of its presence. The reflectivity shown on Figure 4.2a is caused by either turbulent mixing of contrasting thunderstorm outflow and environmental air or by debris kicked up by the accompanying strong gust of air. The reflectivity factor in this case is about 20 dBZ. Observations of clear air convective boundary layer echoes suggest that gust reflectivity factors should usually be larger than -10 dBZ.

Figure 4.2b shows the Doppler velocity field associated with the reflectivity field of Figure 4.2a. The velocity field for this sector scan at a radar elevation angle of 0.4° is showing an abrupt radial wind change at a height 400 m above ground level (AGL). The wind immediately in front (south side of the wind shift line) of the gust shows a component away from the radar or southerly and behind the wind shift line it is toward the radar. The air immediately behind the 4-5 km wide band of approaching air is again southerly although it doesn't show in Figure 4.2b because weaker echoes north of the gust were not displayed. The band of approaching velocities is rather narrow and is connected to a storm 100 km (54 n mi) to the north.

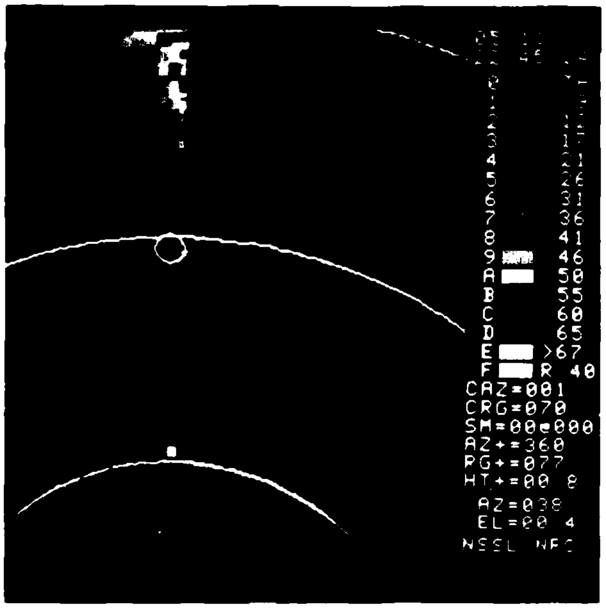

Figure 4.2a *Norman Doppler radar scope photograph of radar reflectivity PPI display showing "thin line" at 2245 CST 11 May 1980. Center of beam is at 0.8 km altitude at range indicated by small white circle.*

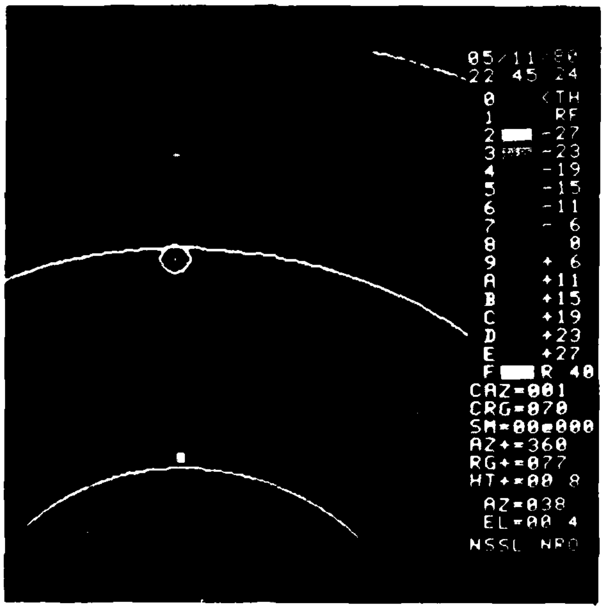

Figure 4.2b *Doppler radial velocity field at the same time as the reflectivity shown in Figure 4.2a.*

Figure 4.3 shows a time sequence of the thunderstorm which generated the gust shown in Figure 4.2b. By extrapolating the positions of the gust and thunderstorm backward in time, we deduced that the portion of the gust, 40 km (22 n mi) northwest of the NRO Doppler radar, coincided with the storm circled in Figure 4.3. Because storm outflows are usually confined to the first kilometer of the atmosphere, they cannot be seen at great distances due to the earth's curvature. The gust in this case was first detected by Doppler radar when it was about 65 km (35 n mi) away and after it had propagated over 40 km (22 n mi) from the storm.

The first detection of gust fronts are conditioned by several factors: 1) the gust front reflectivity, its 2) height and 3) range, and radar characteristics of 4) transmitted power, 5) receiver sensitivity, and 6) beam elevation angle. Usually, beam elevation is one-half a beamwidth above 0° in order to clear obstacles blocking the beam and to minimize beam pattern deformation caused by surface reflections. In the case under discussion, the beam center was at 0.4° elevation angle and for a target at 65 km (35 n mi), places the location of maximum detection sensitivity at about 700 m (230 ft) AGL. Because, as we show later, the gust was confined to altitudes below 700 m (2,300 ft), it is no surprise that the gust was not evident earlier than 2226 CST.

Figure 4.4 shows isochrones for the gust as determined by Doppler radar observations. Superimposed on this plot are locations of surface sites where the time of gust passage was determined when surface wind showed a sudden rise. Time of arrival of the front is indicated at each site and good agreement is found between the two independent data sets. The insert in the top left corner depicts the gust position versus time showing the gust was propagating with a relatively uniform velocity of 13 $m \cdot s^{-1}$ (25 kt).

Although NSSL's Doppler radar has relatively small beamwidth (0.8°), its spatial resolution at 30 or 40 km (16-22 n mi) is about 500 m (1,640 ft), too coarse to determine the fine structure of the gust. Fortunately, the gust passed NSSL's instrumented tall (444 m, 1,456 ft) tower (* in Fig. 4.4) so that in situ measurement of the vertical structure of wind as well as temperature was possible. Both these parameters affect aircraft lift in the critical approach phase of landing. Furthermore, the fine resolution of tower wind data can be compared with the radial component measured with Doppler radar.

Figure 4.5 shows the wind direction, speed, vertical velocity, and temperature at various levels on the tower during passage of the gust. It is quite evident that at the upper most level (444 m), the wind was from the south and abruptly switched to a north-northwest direction at about 2308 CST. The wind speed also changes abruptly from 10 $m \cdot s^{-1}$ to 5 $m \cdot s^{-1}$ (20 to 10 kt) in about 4 minutes. Assuming stationarity of gust structure and a propagation speed of 13 $m \cdot s^{-1}$, (26 kt), there is equivalently a 15 $m \cdot s^{-1}$ (29 kt) change in velocity in a horizontal distance of about 3 km (1.6 n mi) or a horizontal shear of $5 \times 10^{-3} s^{-1}$. A horizontal shear of horizontal wind in excess of about $3 \times 10^{-3} s^{-1}$ may significantly affect an aircraft in its approach to a landing (Table 4.1). Furthermore, a vertical shear of horizontal wind in excess of $6.6 \times 10^{-2} s^{-1}$ may also significantly affect aircraft control. Vertical shears of this magnitude are also found in this gust. Finally, we see vertical velocity perturbations larger than ± 3 $m \cdot s^{-1}$ at 444 m altitudes which may also significantly affect aircraft control. Thus, the shears and vertical wind in this gust are significant, even though the gust is some 80 km from its source!

MAY 11, 1980

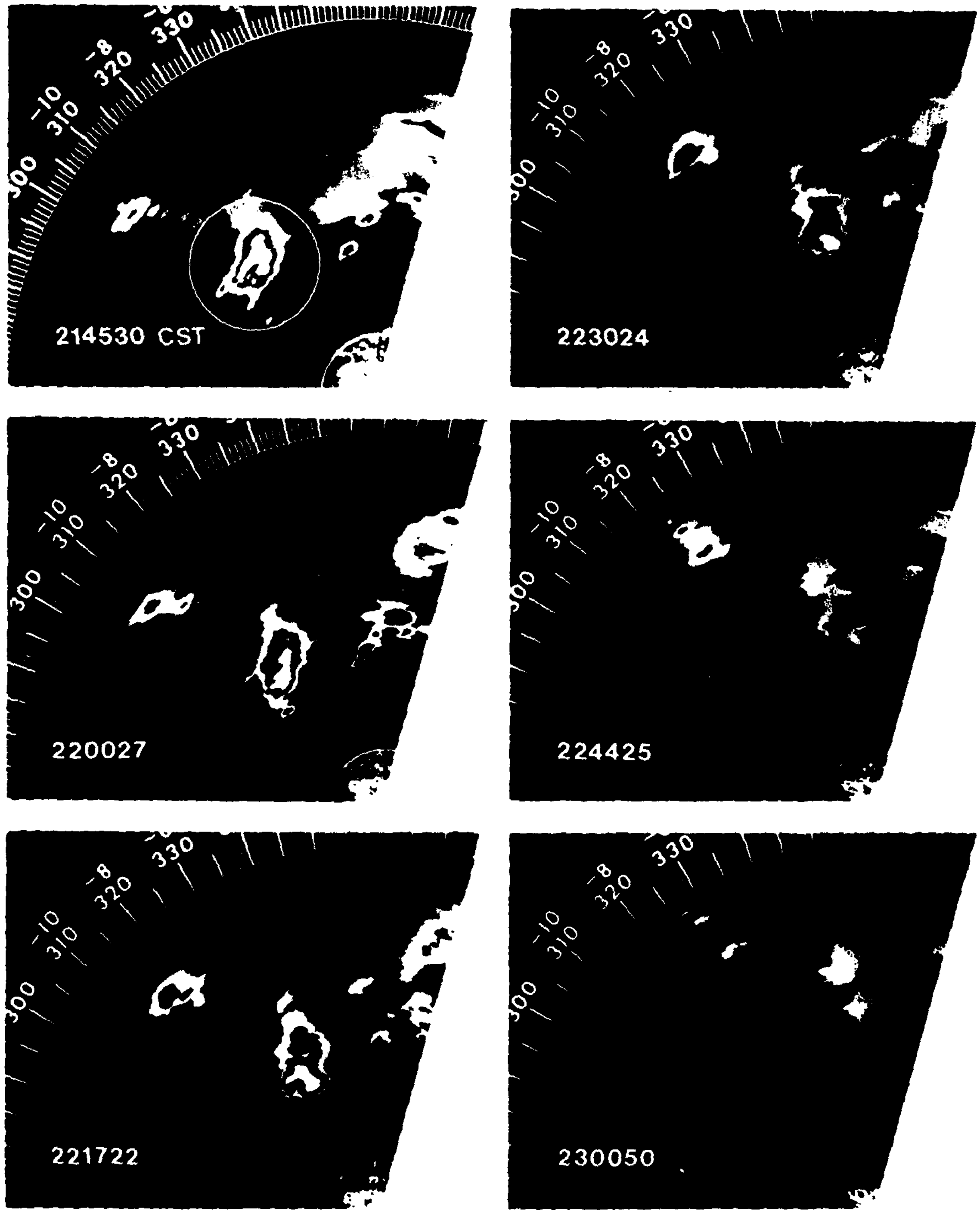

Figure 4.3 *Time sequence of NSSL's WSR-57 radar scope photographs for the thunderstorms on 11 May 1980 which generated the gust front shown in Figure 4.2. Range marks are at 40 km (22 n mi) intervals.*

POSITION OF LEADING EDGE OF WIND GUST
MAY 11, 1980

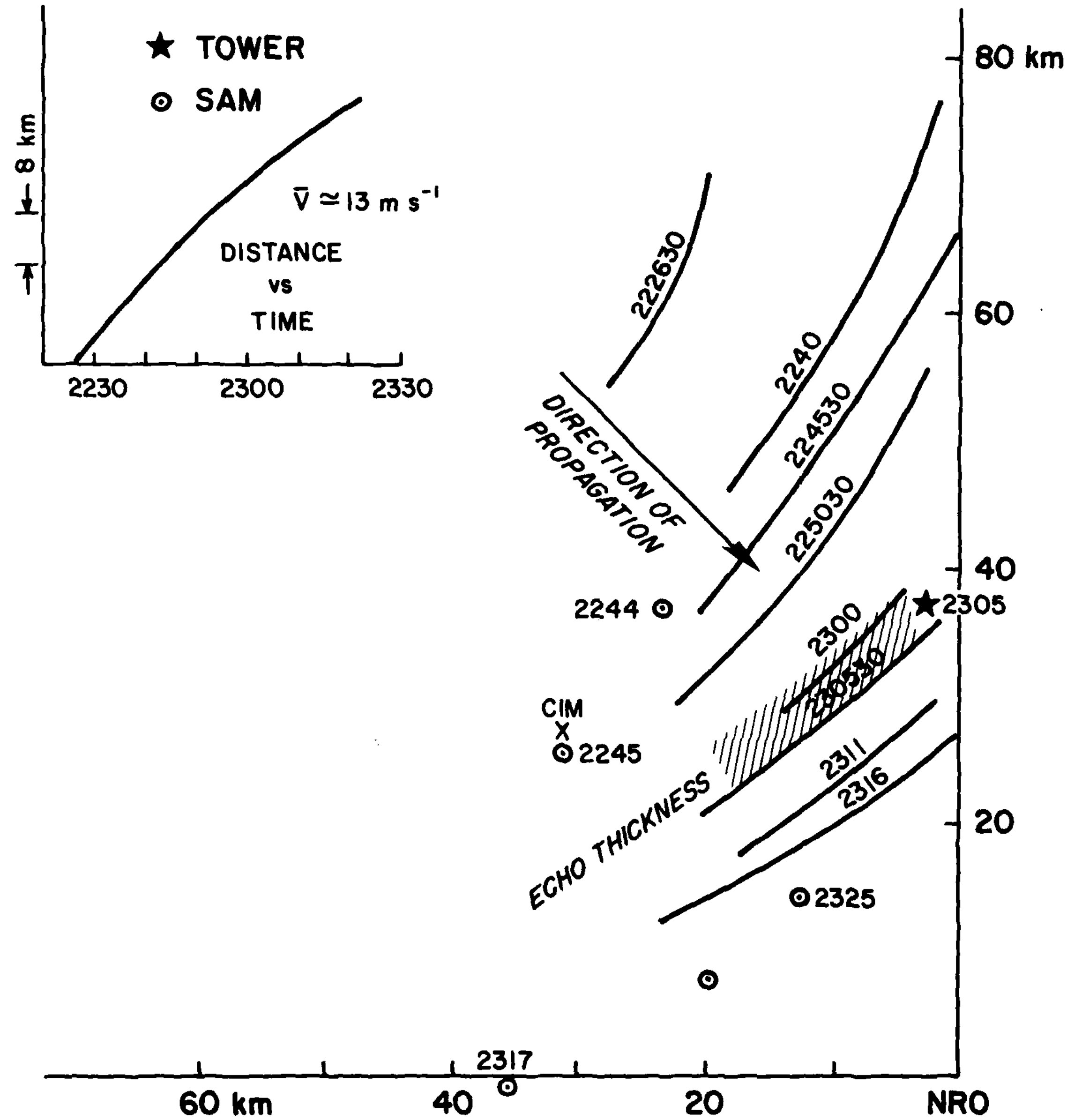

Figure 4.4 *Isochrones (lines of equal time) of gust front movement as determined by NRO Doppler radar.*

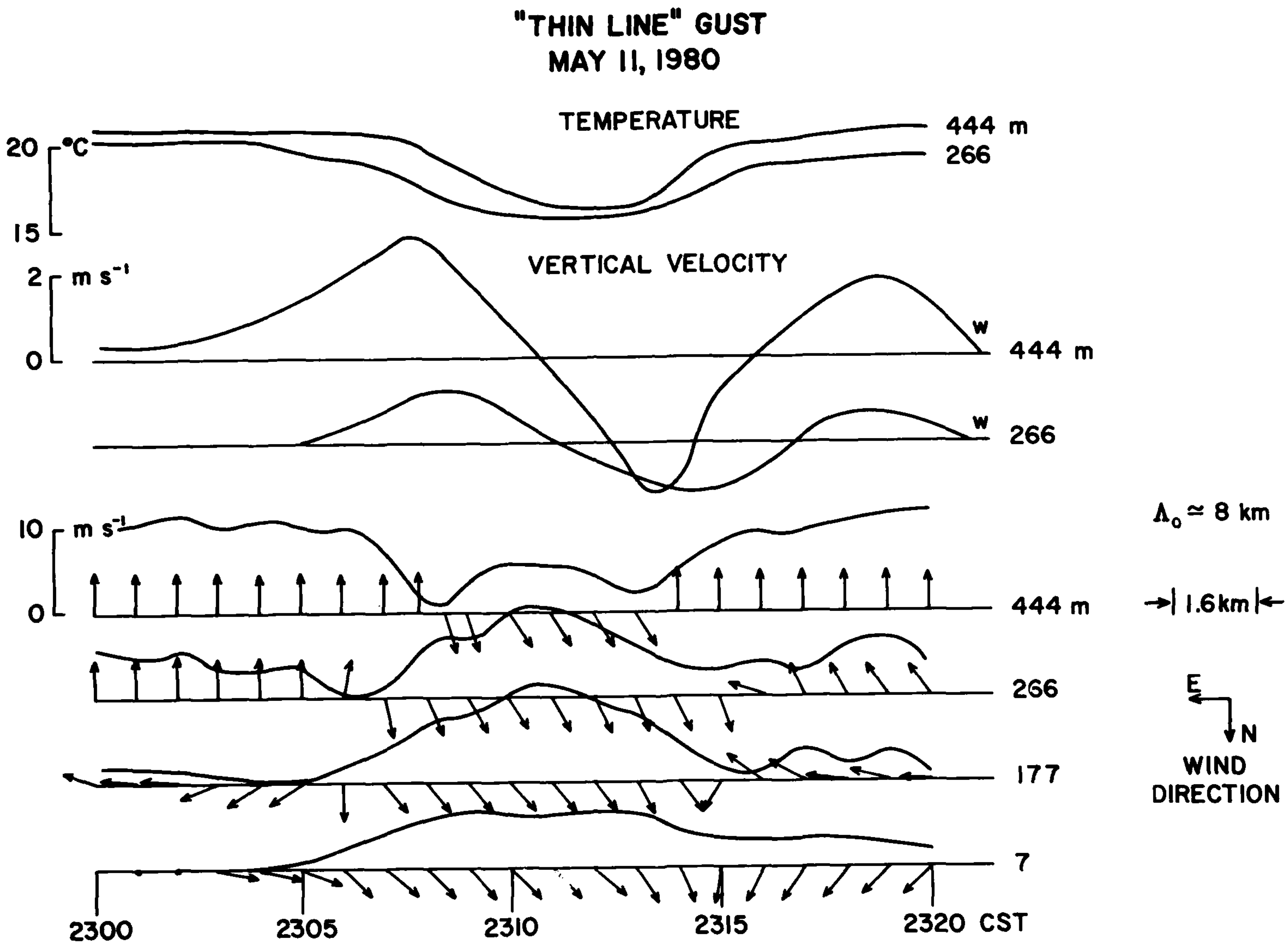

Figure 4.5 *Time-space cross section of wind velocity, temperature, and vertical velocity recorded at 7-levels on the KTVY-TV tower during one gust front passage.*

Table 4.1. Proposed Wind Shear Classifications.*

Intensity of wind shear	Effect on aircraft control	Vertical wind shear	Horizontal wind shear	Updraft/ Downdraft Velocity
Light	Little	0-2 m/s^{-1}/30m	0-2 m/s^{-1}/600m	0-2 m/s^{-1}
Moderate	Significant	2-4 m/s^{-1}/30m	2-4 m/s^{-1}/600m	2-4 m/s^{-1}
Strong	Consider-able difficulty	4-6 m/s^{-1}/30m	4-6 m/s^{-1}/600m	4-6 m/s^{-1}
Severe	Hazardous	>6 m/s^{-1}/30m	6 m/s^{-1}/600m	6 m/s^{-1}

* Submitted to the ICAO Study Group on Low level Shear and Turbulence. This table is being offered to the Communications/Meteorology (COM/MET) Divisional Meeting in April 1982 for inclusion in the WMO's Commission for Aeronautical Meteorology Standards and Recommended Practices.

The surface wind increased from zero and peaked at about 8 $m \cdot s^{-1}$ (16 kt). The temperature trace shows a noticeable drop of 5°C and a return to nearly the ambient temperature as the gust passed the tower.

The structure of the wind and temperature in a northwest to southeast cross section obtained by compositing radar and tower data is shown in Figure 4.6. In this section the gust appears to be a solitary tube of rolling air, but if an observer remains in a frame moving at the propagation speed of the gust [13 $m \cdot s^{-1}$ (25 kt)], the streamlines show the gust to be a cylindrical pocl of cool air that slips southeastward with very little, if any, rolling.

Because the gust appears to be cut off from its source, the long lifetime of this solitary pool of air should indicate that the magnitude of dissipating forces are considerably weak. It's possible that the stable boundary layer without surface based convection in the evening may have allowed the gust a long life. It would be important to establish whether nighttime thunderstorms produce stronger and longer life gust fronts with longer lifetimes.

4.3 June 19-20, 1980 -- Multiple Gust Fronts

The weather conditions of June 19-20, 1980, present a number of interesting features as a group of thunderstorms moved through central Oklahoma during the nighttime hours. Of particular concern was the passage of three cold air outflows or gust fronts between 2200 CST June 19 and 0500Z June 20. Figures 4.7 and 4.8 are photographs of the WSR-57 Plan Position Indicator (PPI) display at 2200 CST and four hours later at 0200 CST when a second line of thunderstorms

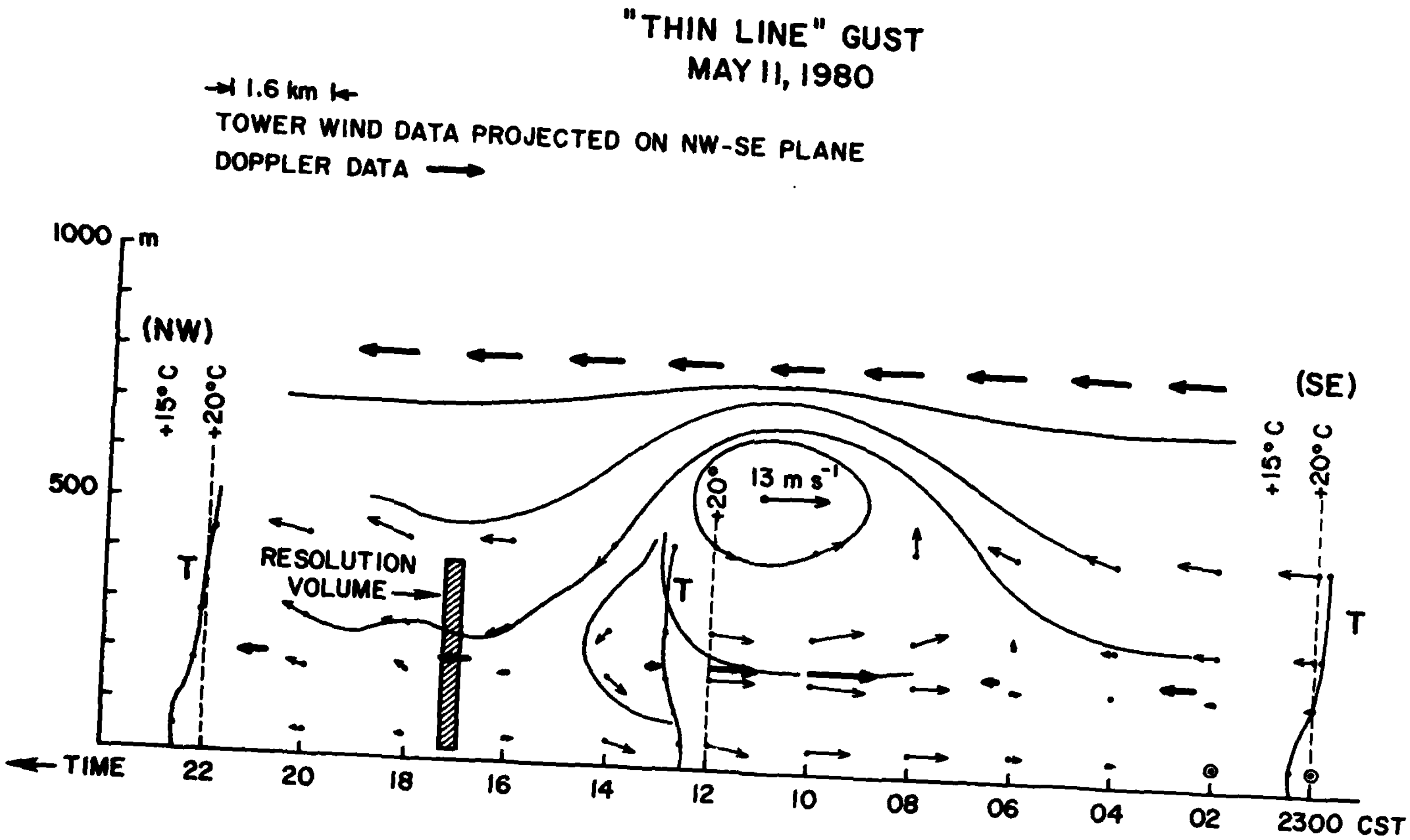

Figure 4.6 *Cross section of gust front melding Doppler radar and tower data.*

Figure 4.7 *Photograph of WSR-57 radar scope for 2200 CST 19 June 1980. 40 km (22 n mi) range marks.*

Figure 4.8 *Radar scope photograph for 0200 CST 20 June 1980. 40 km (22 n mi) range marks.*

approached the Oklahoma City area. The first line can still be seen on the right hand side of the scope as the storms approached Arkansas. On the extreme left (west), we have a third line of echoes just entering the 200 km (108 n mi) range mark. Each of these thunderstorm lines produced a gust front which moved across the surface (SAM) sites. Figure 4.9 a and b show isochrones of (a) time of windshift and (b) time of maximum gust for the first gust front. The maximum gust occurred about 15-20 minutes after the wind shift time. The storm was under surveillance of both the Norman and Cimarron Doppler radars, and an indepth study of the storm and gust front is in progress. The second gust front shown in Figure 4.10 a and b had the strongest winds [32 $m \cdot s^{-1}$ (65 kts)] of the three gust fronts. The third gust front (Figure 4.11 a and b) was followed by what apparently is a cold air downdraft outflow (Figure 4.12), marked by divergence of 10^{-4} to 10^{-3} s^{-1}. These gust fronts are prominent in the tower data time-space cross sections shown in Figures 4.13 and 4.14. Note the rather large downdraft at 2225 CST with values of 6 $m \cdot s^{-1}$ (20 ft s^{-1}) and the updraft stronger than 5 $m \cdot s^{-1}$ (16 ft s^{-1}) occurring 5 minutes later at 2230 CST. This equates to a distance of 1.5 km (about 3/4 n mi.) between the downdraft and updraft at the 444 m level of the tower. For an aircraft on the approach at an airspeed of 93 $m \cdot s^{-1}$ (180 kts), this would produce disconcerting jolts 16 s apart with 10 $m \cdot s^{-1}$ (20 kt) change in the headwind component. These features are being studied in detail.

5. Summary

The 1980 Spring Program witnessed below normal thunderstorm activity; thus, many objectives were only partially reached. The South Dakota School of Mines and Technology's T-28 aircraft had only two data flights before a mishap on the ground terminated the remainder of its flight program. The NASA F-106 aircraft flew 9 data missions. During the initial flights, thunderstorm activity was weak; significant activity occurred only during the last several days of the program. Data from the 16 June 1980 flight have been analyzed. A point-by-point comparison further documents the indicated strong correlation between the spectrum width of the Doppler radial velocity and aircraft encountered turbulence as measured by the departure of the aircraft's vertical acceleration from normal. Work continues on removing the wind shear contribution to the spectrum width.

Several gust front cases were observed. Two cases are discussed. One is a unique occurrence in which a series of three gust fronts move through the Oklahoma City network within a six-hour period. This aptly illustrated that the passage of one severe thunderstorm does not preclude the occurrences of additional storms at the site. If the ambient air mass is not significantly influenced by the thunderstorm, additional storms can occur within several hours time. This case also illustrates the divergent low-level flow beneath a thunderstorm--an area of great interest to pilots.

The second gust front case illustrates Doppler radar's potential for detecting gust fronts. More additional cases need to be acquired to determine the ability for a single radar to provide adequate area coverage of this hazard.

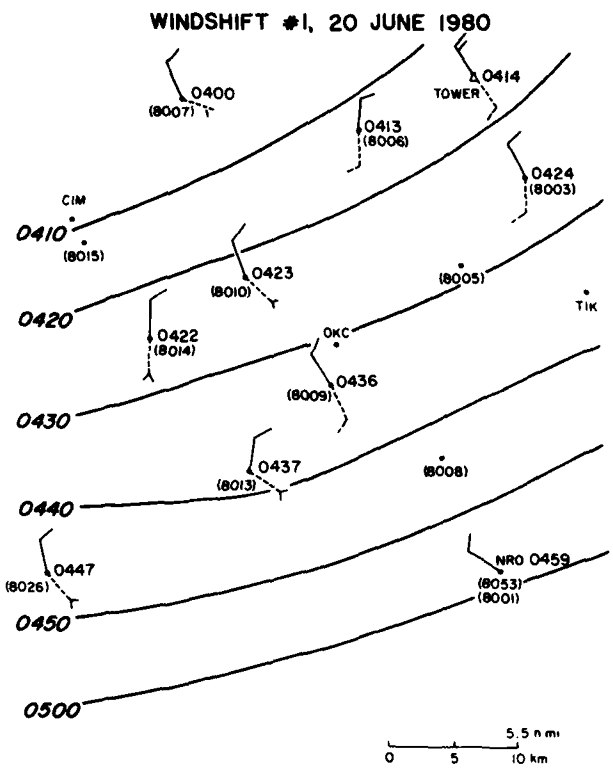

Figure 4.9a *Time of windshift (GMT) as first gust front crosses network. Dashed winds are just prior to passage and solid wind arrows are after passage. Half barb is equal to 5 ft and full barb is 10 kt. Numbers in parentheses are station numbers.*

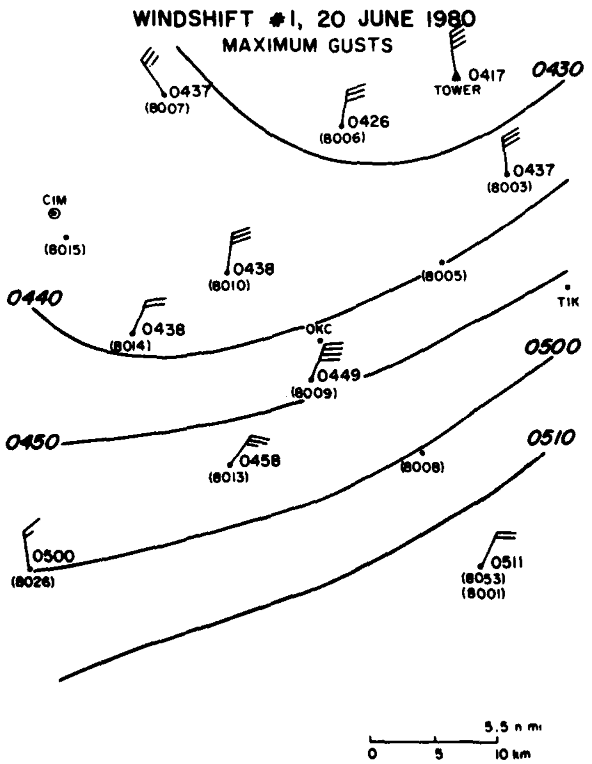

Figure 4.9b *Time (GMT) of maximum gust and strength of maximum gust. (Full barb=10 kt, half barb=5 kt)*

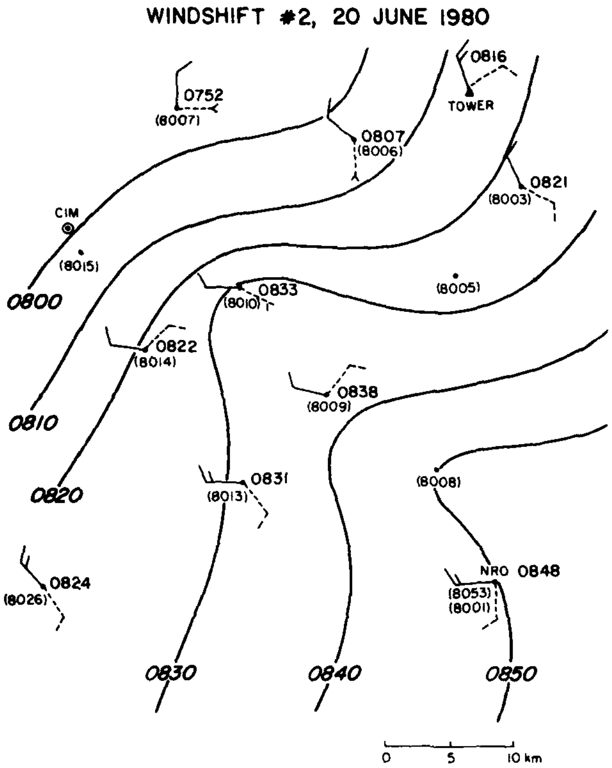

Figure 4.10a *Time of windshift with second gust front. (see Figure 4.9a)*

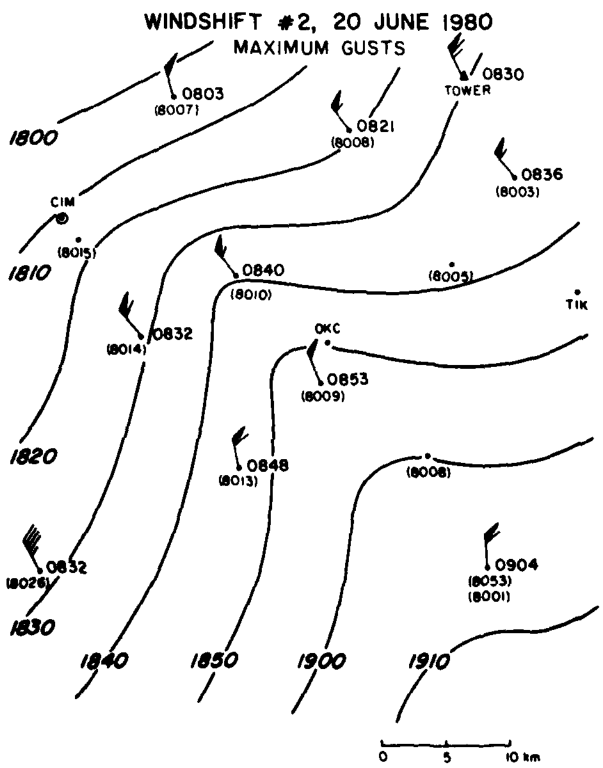

Figure 4.10b *Time of maximum gust and strength of second gust front. (see Figure 4.9b)*

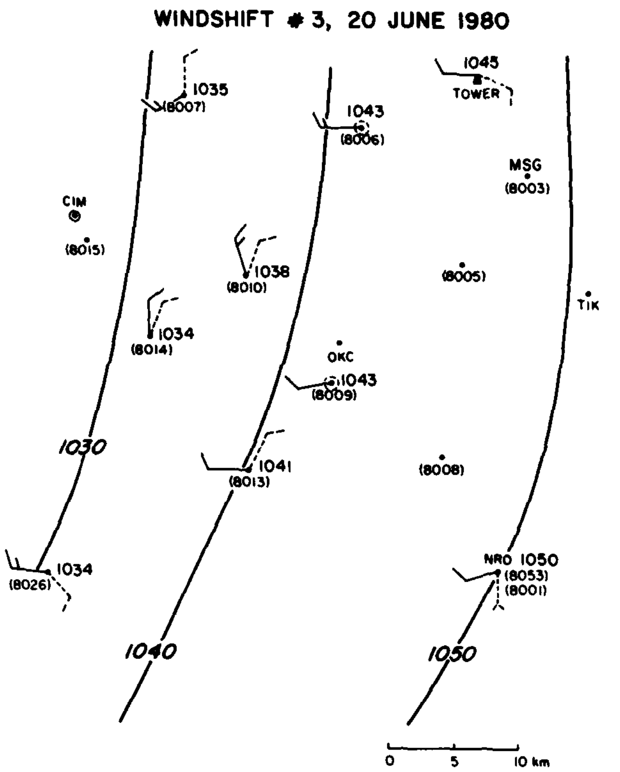

Figure 4.11a *Time of windshift with third gust front. (see Figure 4.9a)*

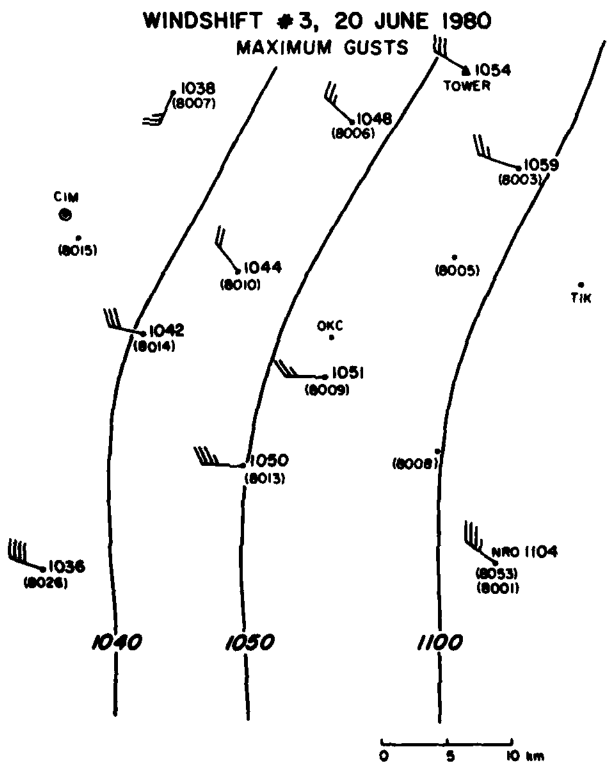

Figure 4.11b *Time and strength of maximum gusts for gust #3. (see Figure 4.9b)*

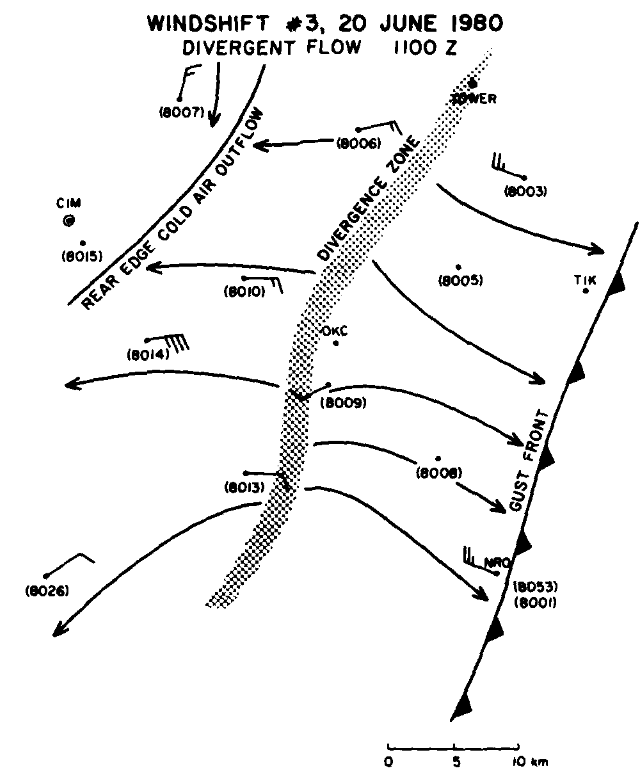

Figure 4.12 Apparent cold air divergent flow beneath thunderstorm associated with gust front.

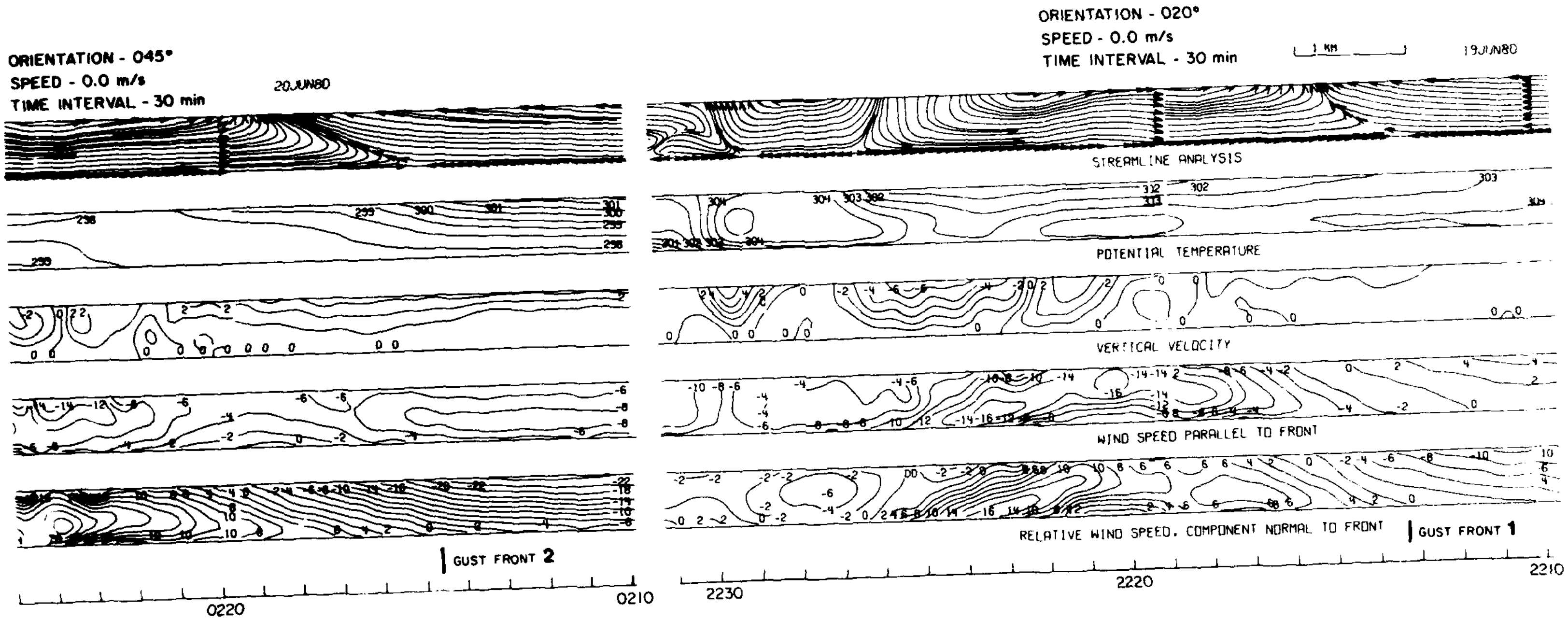

Figure 4.13 *Time-space cross section of gust front as it passed instrumented tower 19-20 June 1980. Time CST*

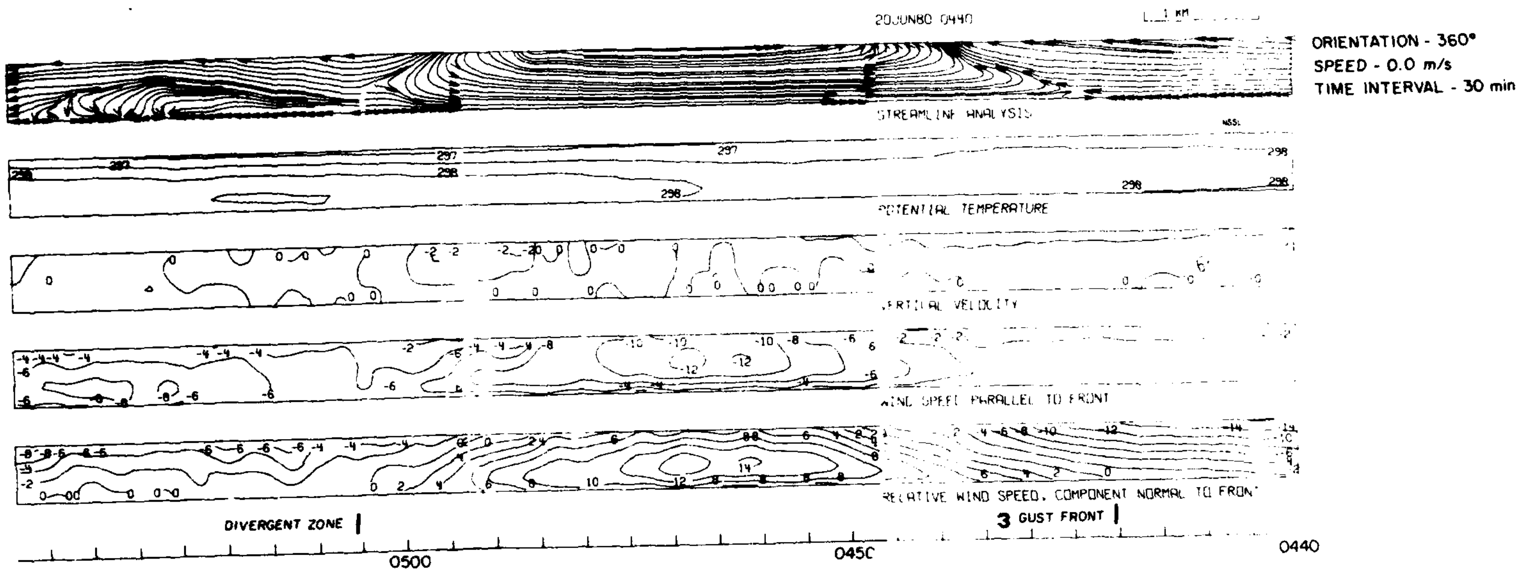

Figure 4.14   Same as 4.13 except later time.

APPENDIX A

Weather and Activity Summary During 1980 Aircraft-Radar Period

May 1	Air traffic controller, Mr. James Trowbridge, assigned to program.
May 2-8	No significant weather.
May 9	T-28 arrived in Norman.
May 10	No significant weather.
May 11	Thunderstorms developed late afternoon over Oklahoma Ctiy. Thin line (wind gust) seen on Doppler radar. Wind shear line at 2300 CST with wind reversal over small area--tower and radar coverage.
May 12	T-28 ready for flight missions. Most activity too far to east for sampling.
May 13, 14	Clear.
May 15	Overrunning rain showers produced heavy rain and low ceilings (6-800 ft overcast). Radar surveillance maintained during day. The low ceilings persisted and the T-28 did not take off. However, no thunderstorms developed and a U-2 overflying central Oklahoma was redirected to central Texas to obtain lightning flash observations.
May 16	No thunderstorms in area.
May 17	No thunderstorms in area during daylight hours. Thunderstorms moved in from west in evening. Tower and LLWSAS data collected around 2300 CST. Gusts to about 25 $m \cdot s^{-1}$ (50 kts) observed with gust front.
May 18	Cold front between Oklahoma City and Ardmore, Okla. Thunderstorms formed a front around 1400 CST and T-28 made 4 penetrations during the afternoon.
May 19	No thunderstorms in area.
May 20	Light thunderstorms in area north of Norman at 0730 CST. T-28 took off at 0945 CST and made 4 penetrations of a moderate thunderstorm about 75 km (40 n mi) west of Norman. After completion of the penetrations, the aircraft returned to Norman. After landing and while taxiing to the ramp area, the aircraft ran off the taxiway onto soft ground. The nose wheel collapsed when it sank into the ground. Major engine damage occurred, and the T-28 program was cancelled for the rest of the season.

May 21	Weak thunderstorms in area.
May 22-24	No thunderstorms in area.
May 25	No thunderstorms in immediate area--some thunderstorms moved to within 140 km (75 n mi) by 2200 CST before dissipating.
May 26	No thunderstorm in area.
May 27	Thunderstorm moved into area 0200 CST and though still active at 0600 CST they decreased at 0900 CST.
May 28	Clear and hot. Thunderstorms developed late afternoon in Texas panhandle moving into western Oklahoma about 2030 CST reaching Oklahoma City about 0130 CST 29 May. F-106 blew a tire in St. Louis on the way from Langley to Tinker AFB.
May 29	Moderate thunderstorm activity in area. F-106 still in St. Louis.
May 30	Thunderstorms formed during the afternoon and evening in west and southwest Oklahoma but did not move into Doppler range. F-106 arrived at Tinker AFB.
May 31	No thunderstorms.
June 1-2	No thunderstorms.
June 3	Weak thunderstorm activity east of Norman; F-106 made 2 penetrations no turbulence, no lightning encountered.
June 4	Weak thunderstorms 90 km (49 n mi) northeast of Norman; F-106 flew one mission encountering no turbulence or lightning.
June 5-7	No thunderstorms.
June 8	Early morning thunderstorms remained active, and the F-106 made penetrations of thunderstorms 140-200 km (75-108 n mi) southeast of Norman at 0945 CST. Thunderstorms decreased rapidly, and F-106 pilot reported light-to-moderate turbulence.
June 9	Weak thunderstorms morning and afternoon; F-106 flew two missions. No turbulence or lightning reported.
June 10-11	No thunderstorms in area.
June 12	Weak early morning thunderstorm. F-106 made penetrations, and pilot reported smooth flight and no lightning.
June 13-16	Clear.
June 16	Moderate-to-severe thunderstorms 90 to 120 km (49-65 n mi) north and northwest of Norman were penetrated by the F-106 in a mid-morning flight. Aircraft experienced moderate to severe turbulence. Lightning was very active but no strikes were recorded on the aircraft.

June 17	The F-106 departed at 0945 CST and encountered moderate turbulence and on the third penetration was struck by lightning. According to plans, the aircraft immediately returned to Tinker AFB to determine if all lightning recording equipment was functional as required. A second mission at 1600 CST resulted in two more lightning strikes for the record. Light-to-moderate turbulence was reported by the pilot.
June 18	Moderate thuderstorms in area--F-106 had blower trouble and was not available for flight.
June 19	No thunderstorm in area during day. F-106 returned to Langley Field, Virginia. Thunderstorms did form during the late evening with one gust front passage at 2200 CST and another at 0200 CST on the 20th. Dual Doppler data recorded during the first gust front passage.
June 20	Activity early morning before daybreak (see above). No thunderstorms in afternoon.
June 21	No thunderstorms in area.
June 22	No thunderstorms during daylight hours.
June 23	Clear. Season ended.

APPENDIX B

Aircraft Daily Summary

1980

May 9 T-28 arrived in Norman.

May 12 T-28 ready for flight operations.

May 15 U-2 flew an afternoon mission arriving in the Oklahoma area near 1515 CST. Some thunderstorm activity was in the state, but lightning activity was very low. Thunderstorm activity was better developed in central Texas, so the aircraft left the area about 1600 CST to reconnoiter thunderstorms in the Austin area.

May 18 T-28 took off at 1524 CST and proceeded south of Norman to a group of thunderstorms about 130 km (70 n mi) away. The first penetration was aborted as the cell intensity in the flight path increased to more than 50 dBZ. The T-28 flying at 10,000 ft MSL made two north-south penetrations just west of the maximum reflectivity associated with the storm complex's westernmost cell. Light-to-moderate turbulence was reported. A second series just to the east of the maximum reflectivity was then flown. The aircraft on these two north-south penetrations (also at 10,000 ft. MSL) experienced moderate turbulence. The T-28 then returned to Norman as the onboard fuel supply dictated.

May 20 The T-28 took off at 0945 CST to intercept thunderstorms 80 km (43 n mi) west of Norman. The first penetration was at 12,000 ft MSL through a storm with a 45 dBZ minimum reflectivity. Light-to-moderate turbulence was encountered and 1/2 inch of ice built up on the wings. A penetration on a return heading resulted in a similar report. The aircraft was then placed at 14,000 ft MSL and the penetration at this altitude was characterized as having moderate turbulence and 6 m s^{-1} (12 kt) up- and down-drafts were reported. Icing was still a problem and the aircraft altitude was lowered to 10,000 ft MSL to melt the ice. This fourth and last penetration for the day also encountered moderate turbulence. The aircraft returned to Norman at 1129 CST and after landing, ran off the taxiway onto soft ground resulting in nose wheel collapse and engine damage. Repair time schedule was such that no further T-28 flight could be made this spring.

May 30 F-106 arrived at Tinker AFB.

June 3 F-106 flew two penetrationsat 22,000 ft MSL through a weak (25 dBZ) storm 40-50 km (22-27 n mi) east of Norman during the period 1420-1520 CST. Only light turbulence was reported and no lightning was sighted.

June 4 F-106 between 1300 and 1400 CST made five penetrations at 20,000 ft MSL of storms 40° at 45-50 km (24-27 n mi) from Norman. Only light turbulence and no lightning was encountered.

June 6 The F106 was flown on an instrument check flight which included a coordinated 5000 ft. MSL flight along a radial toward the Doppler radar for comparison of Doppler and aircraft winds. The aircraft then made three runs by the KTVY-TV tower at top-of tower height to compare aircraft temperature and wind observations with those recorded at 1 s intervals at the tower.

June 8 The F-106 flew one flight from 0945 CST to 1100 CST. The first penetration of a storm at 120° 150 km (81 n mi), made at an altitude of 20,000 ft MSL, reported moderate turbulence. The second penetration was made at 23,000 ft MSL with only light turbulence encountered. The remaining two penetrations were made at 20,000 ft MSL. Light turbulence and no lightning characterized these runs.

June 9 Two F-106 flights were made; one at 0835-0935 CST and the second at 1530 to 1630 CST. The aircraft was flown through areas of high lightning activity in order to be struck. On the first flight two penetrations were made at 13,000 ft. MSL on a storm 130° 170 km (92 n mi). No turbulence and no lightning strikes were encountered and so the aircraft returned to base station. The second flight intercepted a thunderstorm at 280°-290° at 60-80 km (32-43 n mi). One penetration was made at 13,000, two at 14,000, and one at 23,000 ft. No lightning strikes occurred and turbulence was only light.

June 12 An early morning F-106 flight from 0830 CST to 0930 CST made three penetrations at 15,000 ft MSL on a 30-35 dBZ storm located 320° 160 km (86 n mi) from Norman. The pilot reported only light turbulence and no lightning strikes.

June 16 The F-106 flew 0909-1010 CST making 6 penetrations at 15,000 ft on a storm system 340° 130 km (70 n mi) Norman. Moderate-to-severe turbulence was encountered of the aircraft; the aircraft was not struck. Upon return to Tinker AFB, it was discovered that the turbulence had opened a leak in the secondary hydraulic system, and the aircraft was grounded for the remainder of the day.

June 17 Two flights were accomplished by the F-106. The first, from 1052 to 1200 CST, penetrated two storms--one at 360° 100 km (54 n mi) and a second at 90° 120 km (65 n mi) from Norman. On the first pass at 16,000 ft MSL only light precipitation and light turbulence was encountered. So attention was shifted to the second storm. Two penetrations at 16,000 ft MSL were made. Light-to-moderate turbulence was reported and on the last run the aircraft received a direct lightning strike on the boom. The discharge traveled along the left side of the fuselage, and left wing and exited near the left wing tip. The second flight for the day was made from 1600 to 1715 CST on storms 45° 160 km (86 n mi) from Norman. Again the penetration altitude was 16,000 ft MSL. Light-to-moderate turbulence was encountered, and very frequent lightning activity was reported. On the first penetration, the lightning struck near the nose boon and split down both sides of the aircraft. Light-to-moderate turbulence was reported. While lightning activity was present on the third and fourth penetrations, no strikes were recorded. Light-to-moderate turbulence was reported.

June 19 F-106 returned to Langley Research Center, Virginia.

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